Living near the edge: How extreme outcomes and their neighbours drive risky choice

Elliot A. Ludvig[1], Christopher R. Madan[2,3], Neil McMillan[4], Yaqian Xu[4,5,6], & Marcia L. Spetch[4]

[1]Department of Psychology, University of Warwick, Coventry, United Kingdom

[2]Department of Psychology, Boston College, Chestnut Hill, MA, USA

[3]Department of Psychology, University of Nottingham, Nottingham, United Kingdom

[4]Department of Psychology, University of Alberta, Edmonton, AB, Canada

[5]Department of Neurology, West China Hospital, Sichuan University, Chengdu, Sichuan, China

[6]Mailman School of Public Health, Columbia University, New York, NY, USA

Correspondence should be addressed to:

Elliot A. Ludvig
Department of Psychology
University of Warwick
Coventry, UK, CV4 7AL

Email: e.ludvig@warwick.ac.uk
Phone: +44 (024) 765 23151

Abstract

Extreme stimuli are often more salient in perception and memory than moderate stimuli. In risky choice, when people learn the odds and outcomes from experience, the extreme outcomes (best and worst) also stand out. This additional salience leads to more risk-seeking for relative gains than for relative losses—the opposite of what people do when queried in terms of explicit probabilities. Previous research has suggested that this pattern arises because the most extreme experienced outcomes are more prominent in memory. An important open question, however, is what makes these extreme outcomes more prominent? Here we assess whether extreme outcomes stand out because they fall at the edges of the experienced outcome distributions or because they are distinct from other outcomes. Across four experiments, proximity to the edge determined what was treated as extreme: Outcomes at or near the edge of the outcome distribution were both better remembered and more heavily weighted in choice. This prominence did not depend on two metrics of distinctiveness: lower frequency or distance from other outcomes. This finding adds to evidence from other domains that the values at the edges of a distribution have a special role.

Keywords: risky choice, decision making, memory, extreme outcomes, edge effects, end values

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In many domains, values that fall at the extreme edges of a distribution can have a privileged psychological status. In perceptual discrimination, for example, people are more accurate with values from the edges of a distribution than with values in the middle of a distribution–variously referred to as the “edge”, “end”, or “bow” effect (e.g., Braida & Durlach, 1972; Lacouture, 1997; Moon, Fincham, Betts & Anderson, 2015). In memory, words paired with the highest and lowest value rewards in a set are better remembered than words paired with intermediate-value rewards (Madan & Spetch, 2012; see also Castel et al., 2016). Along the temporal dimension, items that occur at the edges (i.e., first or last) in a sequence are also better remembered (i.e., primacy and recency effects; Murdock, 1962). Similar edge effects have also been observed in experience-based risky choice, where outcome values at the extremes of the experienced distribution are both better remembered and more heavily weighted in choice (e.g., Madan et al., 2014). Here, in a series of four experiments, we assess the question of why extremes stand out in risky choice, contrasting two separate hypotheses: (1) that extremes stand out because they are close to the edges of the distribution or (2) that extremes stand out because they are distinct from other values.

Across a range of choice tasks, extremes have notable effects on behaviour. For example, when people process a rapidly presented stream of values, the high- and low-value items more strongly capture attention and have greater influence on valuation than more moderate outcomes (e.g., Kunar, Watson, Tsetsos & Chater, 2017; Tsetsos et al., 2012). In consumer choice tasks between items varying on more than one dimension (e.g., price and quality), people sometimes show extremeness aversion, preferring the item in the middle over items that are best on one dimension and worst on the other (Simonson & Tversky, 1992; Tversky & Simonson, 1993). In all of these cases, the items at one or both ends of a set impact behavior differently than items in the middle. Moreover, these effects are not due to the absolute value of the items because shifting the set changes which items have the most impact.

In experience-based risky choice, the outcomes at the extreme ends (highest and lowest) of the experienced distribution of outcomes also play an important role. When making choices that involve these extremes, people are more risk seeking for choices that involve the high extreme than equivalent choices with no extremes and vice versa (Ludvig & Spetch, 2011; Ludvig, Madan, & Spetch, 2014b). In this case, people are drawn to the extreme high value (the best relative gain) and repulsed from the extreme low value (the worst relative loss). For example, people will choose a 50/50 chance of winning 40 points over a certain 20 points, but choose the safe option for the same gamble in the loss domain (e.g., Ludvig et al., 2014b). This pattern of risk seeking for relative gains and losses in experience is opposite to the pattern when people prospectively state their preferences based on explicit descriptions. For these described choices, people typically show the classic *reflection effect* in which they are more risk seeking for losses than for gains (e.g., Kahneman & Tversky, 1979). This *reversed reflection effect* with experience-based choices has now been reported repeatedly in humans (e.g., Konstantinidis, Taylor, & Newell, in press; Ludvig et al., 2014b; Madan et al., 2014) and in other animals (e.g., Heilbronner & Hayden, 2013, 2016; Ludvig et al., 2014a; but see Lakshminarayanan, Chen, & Santos, 2011; Marsh & Kacelnik, 2002). This divergence in choice occurs despite 50/50 odds for the risky options, extending the related finding that rare events appear to be weighted differently when encountered as descriptions than when learned about through experience (e.g., Barron &

Erev, 2003; Hertwig, Barron, Weber, & Erev, 2004; Wulff et al., in press, but see Kellen et al., 2016; Glöckner et al., 2016).

For experience-based choices, biases in memory for the experienced outcomes likely influence choice (Ludvig et al., 2015; Madan et al., 2014, 2017; Stewart, Chater, & Brown, 2006; Weber & Johnson, 2006). Previously, we proposed an *extreme-outcome rule*, whereby overweighting of the extreme outcomes in memory underlies the reverse-reflection effect (Ludvig et al., 2014b). According to this extreme-outcome rule, when risky options lead to the best or worst possible outcomes in a decision context (+40 or -40 in the example above), those extreme values are better remembered (Madan et al., 2014; Madan & Spetch, 2012), similar to the overweighting of peak events in the evaluation of past affective experiences (e.g., Fredrickson, 2000; Kahneman et al., 1993). Consequently, when making a choice, people are more likely to recall the extreme outcome when evaluating the risky option. This biased recall leads to more risk seeking when the best outcome in a given context is a possible outcome of the risky choice and less risk seeking when the risky choice could lead to the worst outcome. Accordingly, the extreme-outcome rule adds to the many factors that influence risky choice, such as decision framing (Tversky & Kahneman, 1981), available alternatives (Stewart et al., 2006; Stewart et al., 2014), outcome recency (Hertwig et al., 2004; Wulff et al., in press), method of elicitation (e.g., Hsee, 1996), and affective content (e.g., Suter, Pachur, & Hertwig, 2016).

This proposed role for memory in risky choice is consistent with growing evidence that memory plays a crucial role in the construction of preferences and the integration of information to guide decisions (e.g., Bornstein & Norman, 2017; Ludvig et al., 2015; Murty, FeldmanHall, Hunter, Phelps, & Davachi, 2016; Palombo, Keane, & Verfaellie, 2015; Shohamy & Daw, 2015; Weber & Johnson, 2006; Wimmer & Shohamy, 2012). The above biases in memory for extreme outcomes have previously been directly linked to the role of extreme outcomes in risky choice (e.g., Madan et al., 2014). After a risky-choice task where outcomes were learned from experience, people were more likely to report the extreme outcomes than the equally-often-experienced intermediate (non-extreme) outcomes when asked which outcome first comes to mind for each risky option. In addition, people systematically misjudged the frequency of the more extreme outcomes (high and low), reporting them as having happened more often than non-extreme outcomes. This overweighting in memory correlated with risk preferences across individuals, consistent with an overweighting of extreme outcomes in memory driving the reversed reflection effect (Madan et al., 2014, 2017).

An important open question, however, is exactly what makes extreme outcomes stand out in choice and memory. One possibility, as supposed by the extreme-outcome rule, is that outcomes at the edges of a distribution (i.e., the best and worst possible) are more memorable than values in the middle of the distribution, merely by being close to the edge positions (Ludvig & Spetch, 2011; Ludvig et al., 2014a; Madan et al., 2014). According to this view, the edges gain psychological prominence because they define the boundaries of a person's experience in the experimental context. People begin the task with little concept as to what might possibly occur in terms of outcomes, and the edges quickly define for people the range of what is possible. The range of possibilities defined by these extremes is important for how people make many choices, including risky ones (e.g., Lim, 1995; Parducci, 1965; Stewart et al., 2006).

The memory literature, however, points to an alternate hypothesis as to why such extreme outcomes are more memorable: their distinctiveness (e.g., Brown et al., 2007). There are many possible ways in which stimuli can be distinctive and stand out in memory. For example, they may come from a different semantic category than other items, appear in a different colour or font, or even create a unique or bizarre image (Hunt & Worthen, 2006). In previous studies of extreme outcomes in risky choice, the extreme outcomes have typically had two properties that could mark them as potentially distinct and more memorable. First, they often occurred less frequently than other outcomes (e.g., Ludvig & Spetch, 2011; Ludvig et al., 2014b; Madan et al., 2014). Second, as opposed to other non-extreme outcomes, the extremes (by definition) only had neighbours on one side. As a result, they were more distant on average from other outcomes, especially given that the outcomes were fairly evenly distributed. This distinctiveness through distance from other neighbouring values is known to influence both the perceptual salience and memorability of an item in an array (e.g., Neath, Brown, McCormack, Chater & Freeman, 2006). In addition, a similar logic based on temporal distance is used by the SIMPLE memory model to explain recency and primacy effects (Brown et al., 2007; Murdock, 1962).

In previous studies of the interaction of risky choice and memory, the extremity and distinctiveness of the extreme outcomes were always confounded (e.g., Madan et al., 2014, 2017). The extreme outcomes were at the ends of the distribution (by definition), but were also distinct because they occurred less frequently and had fewer neighbouring outcomes than non-extreme outcomes[1]. Following the example above (Madan et al., 2014), the non-extreme outcome (0) was common to both risky options, whereas the extreme outcomes (+40 and -40) were unique to the two risky options, appearing less frequently overall. In addition, the extreme

[1] The lone exception is one previous experiment (Exp. 2 in Ludvig et al., 2014) that did use non-overlapping sets of values and found effects on risky choice, but that experiment did use the same absolute numbers in positive and negative domains and did not test memory.

outcomes (+40 and -40) only had one neighbouring outcome 20 points away (the fixed outcome of +20 or -20), whereas the non-extreme outcome (0) had neighbouring outcomes on either side (both higher and lower), also 20 points away. Thus, it is possible that the extreme outcomes stood out in memory relative to the non-extreme outcomes not because of their placement at the edge of the experienced distribution, but rather because they were more distinct than other outcomes.

The two sets of experiments presented here used novel sets of outcomes to systematically test whether it is the distinctiveness of extreme outcomes due to low frequency (Exp. 1) or the distance from neighbouring outcomes (Exp. 2) that can explain the previously observed overweighting of extreme outcomes. Experiments 1a and 1b used high- and low-outcome sets that did not overlap, thus controlling for difference in relative frequency (see Table 1). In Experiment 1a, all outcomes were positive, and in Experiment 1b, all outcomes were negative. Experiment 2a and 2b used larger decision sets to test whether outcomes at the ends of the distribution also need to be distant from other outcomes to be overweighted. In Experiment 2a, the decision set included both gains and losses, and in Experiment 2b, the decision set included only gains (see Table 2). The extreme-outcome rule predicts that in both experiments participants would be more risk-seeking for higher-value decisions than for lower-value decisions and that these behavioral preferences would map onto self-reported memory biases for the extreme risky outcomes. In contrast, the distinctiveness hypothesis predicts that any effects of extreme outcomes should be eliminated if the extremes are made non-distinct, either by reducing the overlap of non-extreme values (Exp. 1) or by adding neighbouring values (Exp. 2). Together, these studies addressed the question of what makes extreme outcomes stand out in choice and memory.

General Methods

The following methods were common to all four experiments in this paper.

Participants. All research was approved by the University of Alberta Research Ethics Board. All participants provided written informed consent and were tested individually in separate rooms, but were recruited and instructed in groups of up to 15. All payments were in Canadian dollars.

Apparatus and Procedure. All testing was performed using Windows PCs running E-Prime. Participants played a computer-based task to earn points that were exchanged for money. On each trial, participants were presented with pictures of one or two visually distinct doors, which they clicked on to obtain an outcome. Clicking a door was immediately followed by removal of the door images and 1.2 s of feedback showing the number of points won or lost and a cartoon graphic of a pot of gold (gains) or robber (losses). Figure 1 shows the images used in Experiment 1a (see also Ludvig et al., 2014b).

The task used a partial-feedback procedure (see Hertwig & Erev, 2009) in which all choices were consequential, and only feedback for the chosen option was provided. The total accumulated points were continuously displayed at the bottom of the screen. Trials were separated by either a 1- or 2-s interval. The experiment consisted of several blocks of choice trials, which were separated by a brief break (an on-screen riddle), and the last block of choice trials was followed by two types of memory tests.

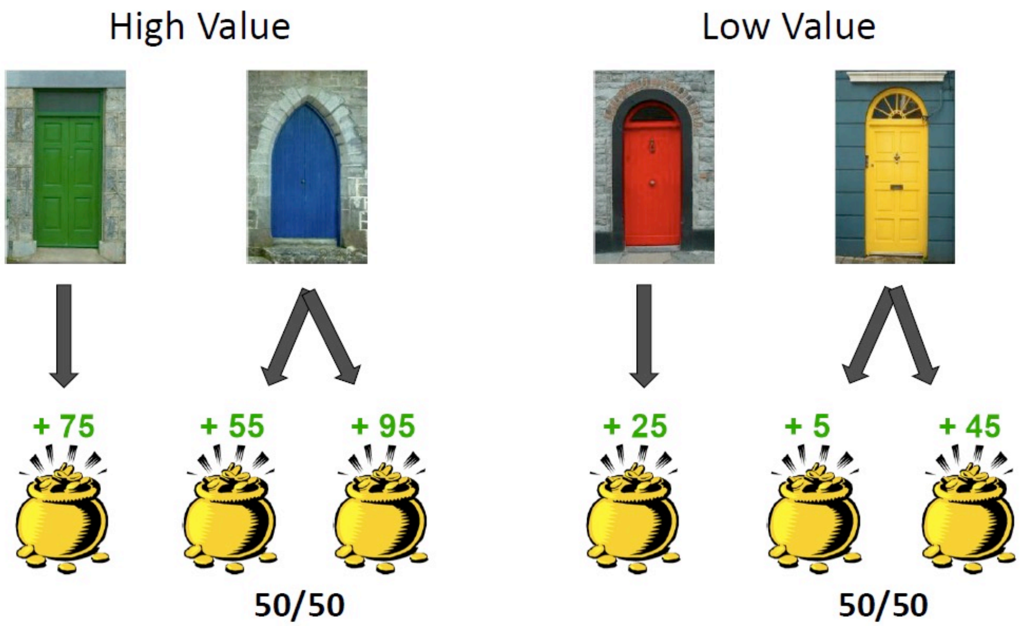

Figure 1. Diagram showing the doors and outcomes used in Experiment 1a. The contingencies between the doors and outcomes were counterbalanced across participants.

In all experiments, clicking on some doors (fixed doors) led to the same outcome every time, and clicking on other doors (risky doors) led to a 50/50 chance of a better or worse outcome. In all cases, the outcomes associated with each door were counterbalanced across participants, and the order of trials varied randomly within blocks. In addition, the left-right location of each door was counterbalanced within each trial type. *Single-option trials* presented only a single door, and the participant was required to click on the door to continue. These trials were designed to ensure that the participants experienced the contingencies associated with each door throughout the experiment regardless of their choices, thereby limiting the possibility that they would perpetually avoid initially unlucky options (i.e., hot-stove effects; Denrell & March, 2001). *Catch trials* presented a choice between one high- and one low-value door (i.e., objectively different expected values) and thereby provided a manipulation check that participants had learned the contingencies and were choosing to maximize points/money. As per our standard practice, all participants who picked the reward-maximizing option on fewer than 60% of the catch trials were excluded from all results (e.g., Ludvig & Spetch, 2011). Finally, the critical trials of interest were *Decision trials.* These provided a choice between a door that yielded a fixed outcome (i.e., a safe door) and a door that provided a variable outcome (i.e., a risky door) of equal expected value (e.g., both high-value doors or both low-value doors). Because the expected value of these doors was equal, these trials provided a measure of risk preference independent of expected-value maximization.

After the choice task, participants' memory for the outcomes of each door was assessed. First, they were presented with each door individually and asked to enter the "number of points [they] first think of" upon seeing each door. This recall test served to assess the accessibility of memory for the outcome(s) associated with each door. The second test was a frequency judgement test, which assessed whether there were any distortions in the remembered frequency of the outcomes. In this test, each door was again presented individually along with a list of the possible outcomes. The participant was asked to type the "percentage of the time the door led to each of the listed outcomes" followed by (except in Exp 1a) a confirmation screen which allowed participants to re-enter their response for that trial. In Experiments 1a, 1b, and 2a, each door was presented with all of the possible outcomes in the experiment listed below the door for these frequency judgments. Based on comments from participants in Experiment 2a about the difficulty of typing in so many values (6 doors and 10 possible outcomes for each), this test was simplified for Experiment 2b by presenting only the 4 risky doors and for each of these doors listing only the two outcomes associated with that door. The first-outcome-reported test always preceded the frequency-judgement test, and the presentation sequence of the doors in each memory test was randomly determined for each participant.

Raw data for all experiments are available at: https://osf.io/wfbnv/. Statistics were calculated using MATLAB (Natick, MA) and JASP (jasp-stats.org), and all inferential statistics were cross-checked with statcheck.io.

Experiment 1

Method

Participants. In Experiment 1a, 58 participants were recruited from flyers posted around the University of Alberta campus (38 female; M_{age} = 25.2, *SD* = 9.3) and were compensated with a $12 honorarium plus a performance-based bonus of up to $8. In Experiment 1b, 56 participants (34 female; M_{age} = 21.0, *SD* = 2.6) were recruited from the University of Alberta psychology participant pool and received course credit plus a performance-based cash bonus of up to $8.

Procedure. Sessions contained six blocks of 48 trials each. In both experiments, there were a total of four doors, with one or two of the doors presented on each trial. In Experiment 1a, participants started with 0 points, and all doors led to gains: a low-value fixed gain (100%: 25 points), low-value risky gain (50%: 5 points; 50%: 45 points), high-value fixed gain (100%: 75 points), and high-value risky gain (50%: 55 points; 50%: 95 points). In Experiment 1b, participants started with 2300 points, and all doors led to losses: a low-value fixed loss (100%: -75 points), a low-value risky loss (50%: -55 points; 50%: -95 points), a high-value fixed loss (100%: -25 points), and a high-value risky loss (50%: -5 points; 50%: -45 points). In this case, participants were instructed to minimize the number of points lost. See Table 1 for a summary.

Each block included eight single-door trials, 24 decision trials, and 16 catch trials. Decision trials equally often involved choices between the two high-value doors or two low-value doors. Two participants in Experiment 1a and one participant in Experiment 1b were excluded based on catch-trial performance. Additionally, one participant was excluded from Experiment 1a for not following instructions (i.e., writing values down, despite explicit instructions not to). The two types of memory tests followed the last block of choice trials.

Data Analysis. Risky choice was calculated as the proportion of choices of the risky option on decision trials (i.e., on the trials in which the choice was between a fixed and a risky option of equal expected value). Risky choice was calculated separately for choices between high-value options and choices between low-value options for each block of trials. All degrees of freedom for within-subjects ANOVA tests were corrected using Greenhouse-Geisser. Consistent with Madan et al. (2014), the average of the last 3 blocks of trials was used to assess stable choice preferences.

Results

Risky choice. Figure 2A presents the mean risky choice for high-value and low-value decisions across blocks in Experiment 1a. Participants were initially close to indifferent between the risky and fixed alternatives on both choices but showed a gradual decrease in risky choice (i.e., risk aversion) for low-value decisions. A 2 x 6 [Value (High, Low) x Block (1-6)] repeated-measures ANOVA showed a significant interaction, $F(3.3,180.5) = 4.38$, $p = .004$, $\eta_p^2 = 0.075$. The main effects of Block, $F(3.6,195.5) = 3.61$, $p = .009$, $\eta_p^2 = 0.063$, and Value, $F(1,54) = 26.4$, $p < .001$, $\eta_p^2 = 0.33$, were also significant. Averaged across the last three blocks (i.e., after sufficient opportunity to learn the outcomes), participants chose the risky option 28.9±3.8 (Mean±SEM) percentage points more often for high-value choices (53.3±4.3%) than for low-value choices (24.4±3.4%); this difference was significant, $t(54) = 5.49$, $p < .001$, Cohen's d = 1.01, and in the direction predicted by the extreme-outcome rule.

Figure 2B shows the mean risky choice for each of the six blocks in Experiment 1b. Again, participants started near indifference on both choices, but showed a gradual decrease in risky choice on the low-value decisions.

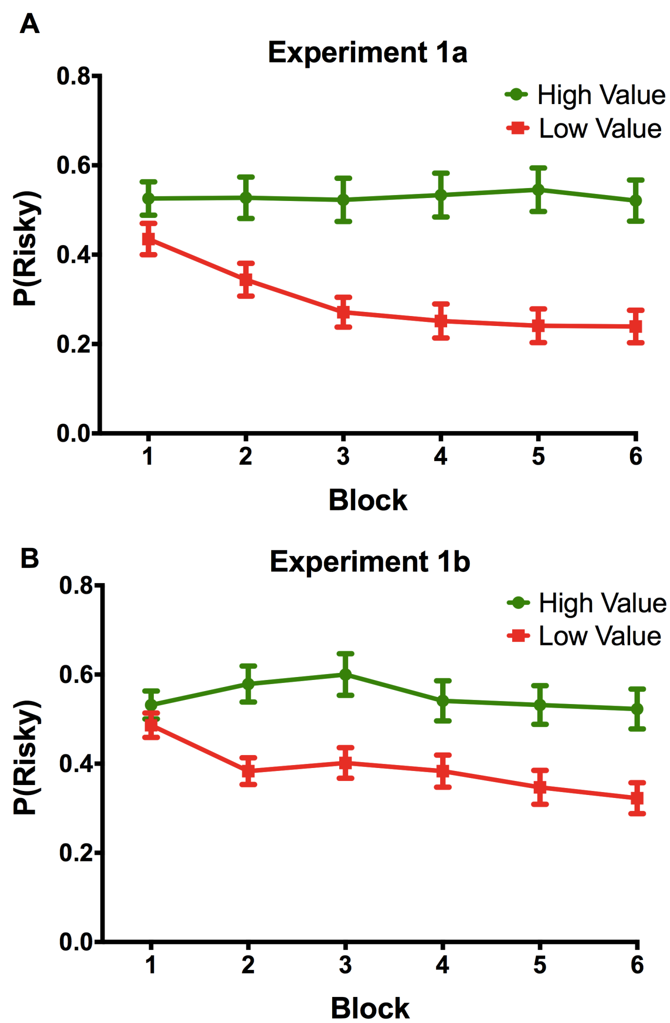

Figure 2. Proportion of choices of the risky option on decision trials between fixed and risky high-value options (green circles) and between fixed and risky low-value options (red squares) for each of the six trial blocks in: (A) Experiment 1a and (B) Experiment 1b. Error bars are SEM.

A 2 x 6 [Value (High, Low) x Block (1-6)] repeated-measures ANOVA showed a significant interaction, $F(4.0, 215.2) = 3.21$, $p = .014$, $\eta_p^2 = 0.056$. The main effect of Block was marginally significant, $F(3.0, 161.2) = 2.67$, $p = .049$, $\eta_p^2 = 0.047$, and the main effect of Value was clearly significant, $F(1,54) = 22.5$, $p < .001$, $\eta_p^2 = 0.29$. Averaged across the last three blocks, participants chose the risky option 18.1±4.2 percentage points more often for high-value choices (53.2±4.2%) than for low-value choices (35.1±3.2%); this difference was significant, $t(54) = 4.26$, $p < .001$, $d = 0.66$, and was again as predicted by the extreme-outcome rule.

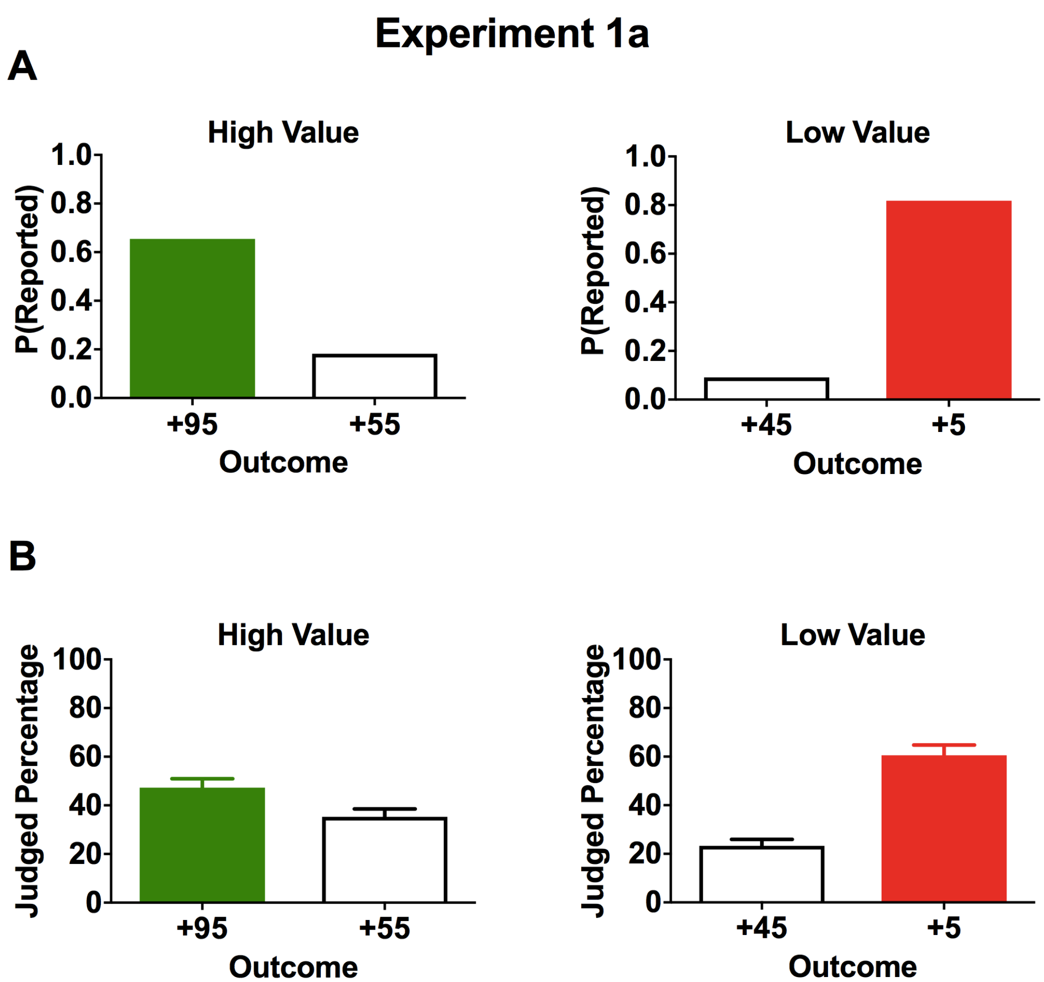

Figure 3. Results from self-report memory tests with the risky doors in Experiment 1a. (A) The proportion of participants who reported the extreme (filled green or red bars) and non-extreme values (white bars) as the "first outcome that came to mind" for each risky door. (B) The judged percentages for each risky door's outcome (±SEM). Note that some participants reported other values for both questions, thus the totals do not sum to 1 (in panel A) or 100 (in panel B).

Post-test memory. Figure 3A shows the frequency of participants' reports of the "first outcome to come to mind" for the high- and low-value risky doors in Experiment 1a. Participants were more likely to report the high extreme value (+95) than the non-extreme value (+55) for the high-value risky door, $\chi^2(1, N=46) = 14.7, p < .001$, and the low extreme value (+5) than the non-extreme value (+45) for the low-value risky door, $\chi^2(1, N=50) = 32.00, p < .001$.

Figure 3B illustrates the average judged frequency of each potential outcome on the risky high- and low-value doors. Even though the risky doors objectively led equiprobably to their outcomes, participants reported the extreme outcomes as occurring more frequently than the non-extreme outcomes. For the high-value risky door, participants rated the extreme outcome +95 as having occurred 12.0±5.8 percentage points more often than the non-extreme outcome +55, $t(54) = 2.07, p = 0.04, d = 0.46$; and for the low-value risky door, they rated the extreme outcome +5 as having occurred 37.3±6.1 percentage points more often than the non-extreme outcome +45, $t(54) = 6.17, p < .001, d = 1.43$.

Figure 4A shows the frequency of participants' reports of the "first outcome to come to mind" for the risky doors in Experiment 1b. Most participants entered all values without negative signs, but because all the numbers in the experiment were negative and participants were not specifically instructed to include the sign, we converted all entered numbers to negative values. Participants reported the extreme outcome (-5) more often than the non-extreme outcome (-45) for the high-value risky door, $\chi^2(1, N=49) = 29.5, p < .001$, and the extreme outcome (-95) more often than the non-extreme outcome (-55) for the low-value risky door, $\chi^2(1, N=44) = 10.8, p = .001$.

Figure 4B shows the judged frequencies of outcomes for the risky high- and low-value doors. Participants reported the extreme outcome as occurring 12.9±4.9 percentage points more frequently than non-extreme outcomes for the high-value risky door, $t(54) = 2.63$, $p = 0.011$, $d = 0.61$, and 28.8±4.6 percentage points more frequently than the non-extreme outcome for the low-value risky door, $t(54) = 6.30$, $p < .001$, $d = 1.33$.

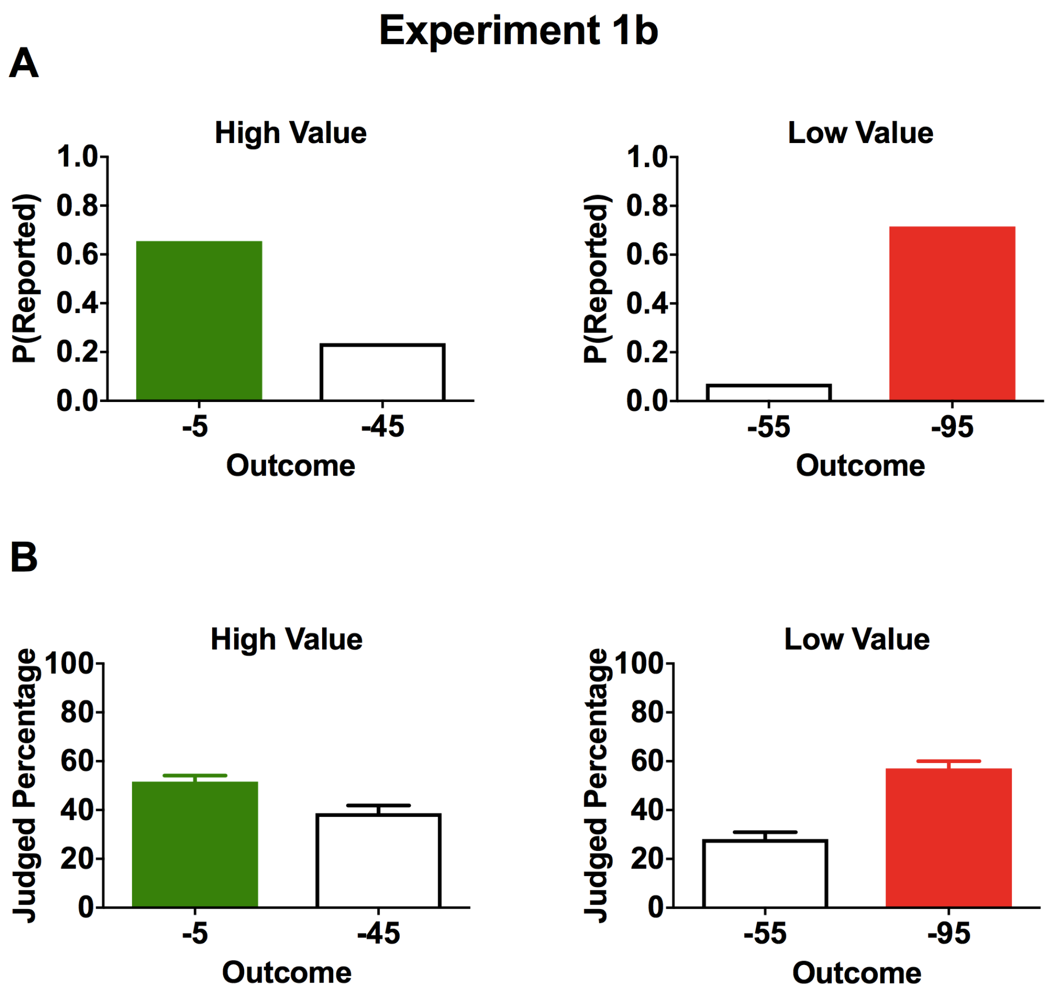

Figure 4. Results from self-report memory tests with the risky doors in Experiment 1b. (A) The proportion of participants who reported the extreme (filled red or green bars) and non-extreme values (white bars) as the "first outcome that came to mind" for each risky door. (B) The judged percentages for each risky door's outcome (±SEM). Note that some participants reported other values for both questions, thus the totals do not sum to 1 (in panel A) or 100 (in panel B).

In both experiments, for both high and low values, frequency judgements were significantly correlated with risky choice, consistent with Madan et al. (2014; 2017). To ensure that correlations between risky choice and memory judgments were not solely due to differences in how often each outcome was experienced, memory judgments and risk preference were correlated after controlling for the actual incidence rates of the outcomes for the risky doors across all trials in the experiment (i.e., a partial correlation; see Madan et al., 2014).

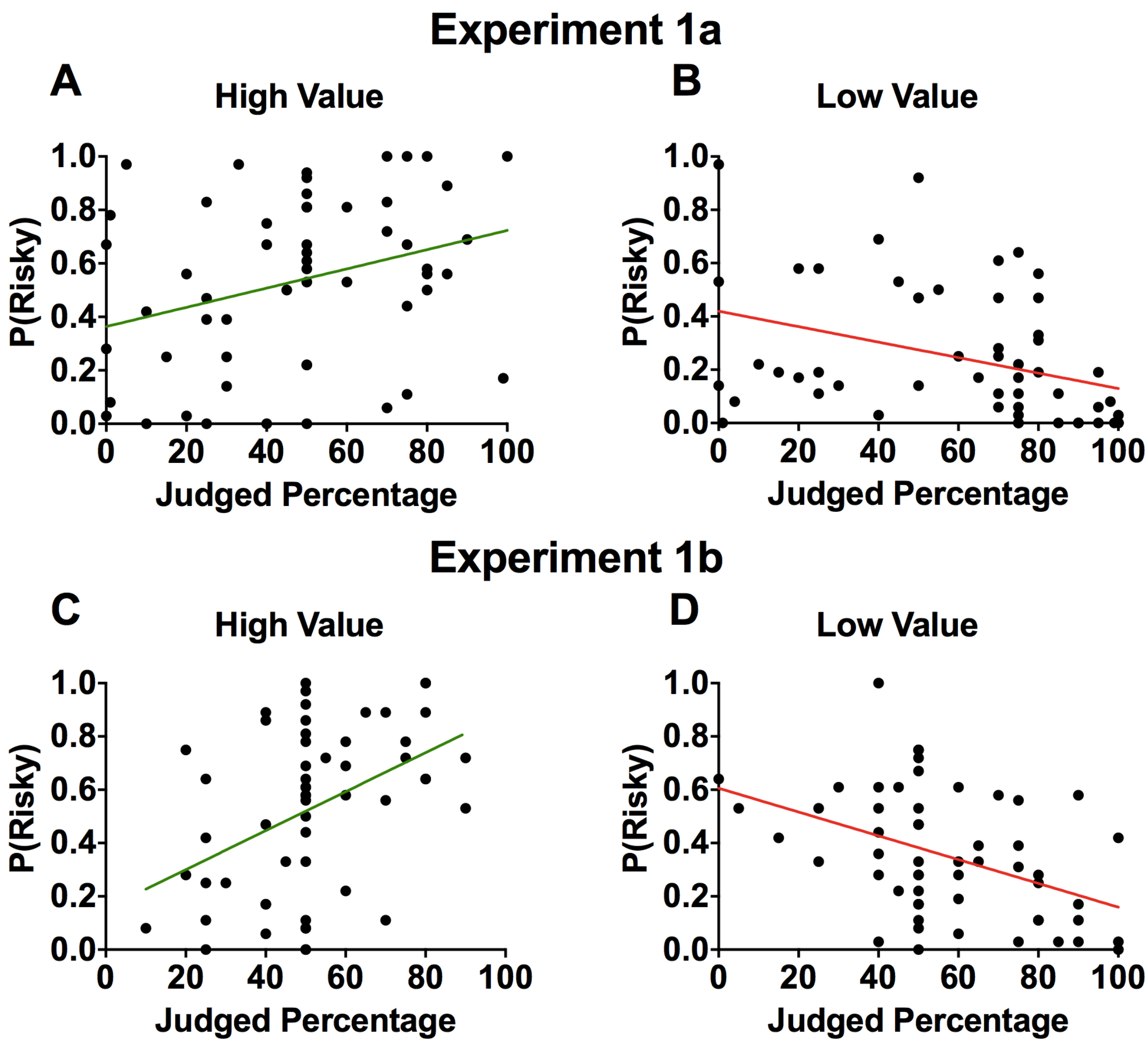

Figure 5. Scatterplots of the proportion of risky choices (averaged over last three blocks) as a function of the judged frequency of the extreme door for (A) high-value doors and (B) low-value doors (right) in Experiment 1a. (C-D) Same scatterplots for Experiment 1b. Each dot represents an individual participant.

Figure 5 shows the correlations between the frequency judgments and risky choice for both Experiments, split by high (Figs 5A and 5C) and low values (Figs 5B and 5D). In Experiment 1a, there was a marginally significant positive correlation between risky choice and judged frequency of the extreme outcome for high-value choices (+95), $r_p(52) = .28$, $p = .044$. For low-value choices, there was also a significant negative correlation between risky choice and judged frequency of the extreme outcome (+5), $r_p(52) = -.33$, $p = .017$. In Experiment 1b, there was again a significant positive correlation between risky choice and the judged frequency of the high extreme (-5), $r_p(52) = .44$, $p = .001$, and a significant negative correlation between risky choice and the judged frequency of the low extreme (-95; worst possible outcome), $r_p(52) = -.44$, $p = .001$. Too few participants in either experiment reported the non-extreme outcomes to perform appropriately-powered correlations of first-outcome self-reports with risky choice.

Discussion

These experiments showed that the most extreme outcomes in a decision context are overweighted both in risky choice and in post-choice memory judgements. These experiments resolve an ambiguity in previous studies showing a link between memory biases and the reverse-reflection effect (e.g., Madan et al., 2014; 2017); in those studies, the non-extreme outcomes overlapped and were also associated with both the high- and low-value risky choices. As a result, in those studies, the non-extremes occurred more frequently than extreme outcomes. The outcome distribution used here did not contain overlapping outcomes, yet an extreme-outcome effect still emerged. These results support the hypothesis that outcomes at the edge of the distribution of experienced outcomes are overweighted in both choice and memory, and importantly, they explicitly rule out distinctiveness due to a lower frequency of occurrence as the reason for this effect of extreme outcomes.

Moreover, the comparable results across both experiments indicate that overweighting of extreme outcomes does not depend on absolute properties of the extremes, such as absolute numerical value or distance from zero. In Experiment 1a, the high extreme was +95 and the low extreme was +5, whereas in Experiment 1b, the high extreme was -5 and the low extreme was -95 (see Table 1). In both cases, participants chose the risky option more often for high-value decisions than for low-value decisions, consistent with previous demonstrations (Ludvig & Spetch, 2011) and in contrast to the standard reflection effect (Kahneman & Tversky, 1979).

Finally, self-report memory judgments made after testing suggested that most participants over-represented the extreme outcomes in memory. Most participants reported the extreme outcomes as the first that came to mind for each risky door, and the extreme outcome was judged as having occurred more often than the non-extreme outcome; the latter judgments correlated with actual risky choices that participants made during the task. This corresponds with the suggestion made previously (Ludvig et al., 2014b; Madan et al., 2014) that participants over-sample extreme outcomes from memory and thus overweight these outcomes in their risky decisions.

Experiment 2

Experiments 1a and 1b showed overweighting of outcomes at the ends of the distribution across different sets of absolute values in choice and memory. These experiments rule out interpretations in terms of differences in the frequency of extreme and non-extreme outcomes. Experiments 2a and 2b further evaluate what makes extreme outcomes stand out by varying the relative proximity of neighbouring values. The extreme-outcome rule hypothesizes that extreme outcomes are salient because they are the largest or smallest in a context, independent of the values of the non-extreme outcomes. A second possibility drawn from the memory literature is that extremity depends on distinctiveness from nearby outcomes (e.g., Brown et al., 2007). By this hypothesis, extreme outcomes are more distinct (and memorable) than non-extreme outcomes because extreme outcomes only have neighbours on one side (either higher or lower), whereas non-extreme outcomes have neighbours on both sides (both higher and lower).

Experiments 2a and 2b assessed these hypotheses by using larger decision sets and varying the proximity of the nearest neighbours to the extreme outcomes across two groups (see Table 2). In particular, in Group Nearby, additional risky options were included which yielded *nearby* outcomes only a single point away from the extreme outcomes. In Group Remote, as a control, additional risky options were included which yielded outcomes that were only a single point away from the fixed outcome, but were *remote* from the extremes.

As per the pre-registration, we tested 5 specific hypotheses with this design. First, for Group Remote, the *Extreme-Outcome-Reliability Hypothesis* predicted the usual extreme-outcome effect (more risk seeking for high-value choices; better memory for extremes), even with the new sets of outcomes. Second, for Group Nearby, there were two opposing predictions: the *Value-Distinctiveness Hypothesis* supposed that extremity depends on distinctiveness in value from nearby neighbours, so the extreme-outcome effect would be reduced in both choice and memory, whereas the *Edges Hypothesis* supposed that extremity only depends on the range of values experienced, so the extreme-outcome effect would be equally strong in this group. Finally, we also tested a secondary set of opposing hypotheses regarding Group Nearby: the *Interference Hypothesis* supposes that neither the extremes outcomes nor the nearby neighbours will stand out in memory or choice, whereas the *Edge-Proximity Hypothesis* supposes that both the extreme outcomes and the nearby neighbours will stand out in memory and choice.

The methods, hypotheses, and analyses for these experiments were all pre-registered on the Open Science Framework (https://osf.io/grj42/).

Method

Participants. Participants were recruited from the University of Alberta Psychology participant pool. They received credit toward their introductory psychology course and a bonus of up to $5 (Canadian) depending on the points earned. In Experiment 2a, 205 participants were randomly assigned to either Group Nearby: n = 100 (63 female; mean age = 19.0) or Group Remote: n = 105 (61 female; mean age = 19.3). In Experiment 2b, 129 participants were randomly assigned to Group Nearby: n= 65 (44 female; mean age = 20.5) or Group Remote: n =64 (50 female; mean age = 20.8).

Procedure. The procedure was similar to that used in Experiment 1 except that there was a total of six doors that provided the choice options and 10 possible outcomes as outlined in Table 2. In both experiments, two of the doors always led to *Fixed* outcomes, two of the doors led to *Risky Extreme* outcomes with a 50/50 chance, and the remaining two doors to led to *Risky Neighbour* outcomes with a 50/50 chance.

In Experiment 2a, the decision set included gains and losses. The *Fixed* gain door led to +45 and the *Fixed* loss door led to -45. The *Risky Extreme* doors included one gain door (+15 or +75) and one loss door (-15 or -75). The outcomes for the *Risky Neighbour* doors differed for the two groups: In Group Nearby, the *Risky Neighbour* gain door led to +16 or +74 and the *Risky Neighbour* loss door led to -16 or -74 (i.e., the outcomes were near to those for the extreme doors); in Group Remote, these doors lead to different gain outcomes (+44 or +46) and loss outcomes (-44 or -46). Note that all gain doors had an expected value of +45 and all loss doors had an expected value of -45.

In Experiment 2b, the decision set included high- and low-value gains. The *Fixed* high-value door let to +75, and the *Fixed* low-value door led to +25. The *Risky Extreme* doors included one high-value door (+55 or +95) and one low-value door (+5 or +45). The outcomes for the *Risky Neighbour* doors differed for the two groups: In Group Nearby, the *Risky Neighbour* high-value door led to +56 or +94 (i.e., one away from the extreme), and the *Risky Neighbour* low-value door led to +6 or +44; in Group Remote, these doors led to different high-value outcomes (+74 or +76) and low-value outcomes (+24 or +26). In this experiment, all high-value doors had an expected value of +75, and all low-value doors had an expected value of +25.

In both Experiments 2a and 2b, the choice task consisted of five blocks of 66 trials, each consisting of 12 single-door trials, 18 catch trials, and 36 decision trials. All decision trials involved choices between options that provided the same expected value: in each block, 12 choices were between an extreme door and a fixed door, 12 were between a neighbour door and a fixed door, and 12 were between an extreme door and a neighbour door. In both experiments, one participant in Group Nearby and two participants in Group Remote were excluded based on catch-trial performance (<60% reward-maximizing choices).

Analyses

Risky choice. The primary dependent measures were the percent risky choice for gain and loss options (Experiment 2a) or the high-value and low-value options (Experiment 2b) averaged over the last 3 blocks. Risky choice was defined as selecting the risky option when pitted against the fixed outcome of equal expected value. The percent risky choice was calculated for both the risky extreme doors and for the risky neighbour doors. As per the pre-registration and as detailed above, three main hypotheses were tested for the risky-choice results:

1. ***Extreme-Outcome-Reliability Hypothesis****: Group Remote will show the extreme-outcome effect (more risk seeking for higher valued outcomes) for risky choices involving the extreme outcomes.*

We conducted paired one-tailed t-tests the *a priori* prediction that for extreme risky choices, Group Remote would show higher risk seeking for gains than for losses (Experiment 2a) and for high-value than low-value choices (Experiment 2b).

2. ***Value-Distinctiveness Hypothesis****: If the effects of extremity depend on distinctiveness in value from nearby neighbours, then the extreme-outcome effect will be stronger in Group Remote than Group Nearby.*

3. ***Edges Hypothesis****: If the effects of extremity are solely defined by the range of values experienced (not distance from neighbours), then the extreme-outcome effect will not be reliably influenced by group*.

Hypotheses 2 and 3 are opposing predictions, and we tested them with a 2x2 mixed-factor ANOVA on the extreme risky choices, with a within-subjects factor of value (gain or loss in Experiment 2a; high or low in Experiment 2b) and a between-subject factor of group (Nearby and Remote).

Finally, we also tested a secondary set of opposing hypotheses[2] regarding the values in Group Nearby:

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[2] Hypotheses 4 (*Interference*) and 5 (*Edge Proximity*) were initially presented as sub-Hypotheses 2a and 2b in the pre-registration. We realized that the logic of our hierarchical hypothesis structure was problematic, however, because Hypothesis 2b could be true regardless of whether

4. ***Interference Hypothesis****: Neither the extremes nor the close neighbours will be treated as extreme outcomes.*

5. ***Edge-Proximity Hypothesis****: Both the extremes and the close neighbours will be treated as extreme outcomes.*

We tested the additional predictions from Hypotheses 4 and 5 about the neighbour doors with an additional 2x2 (Value x Group) mixed-factor ANOVA on the neighbour risky choices.

Memory Tests. The two measures of memory (first outcome reported and frequency judgments) were analyzed separately for the gain and loss risky doors (Experiment 2a) and for the high-value and low-value risky doors (Experiment 2b). For the first outcome reported, only data from those who reported one of the two outcomes associated with the door were included in the statistical analysis, and the responses were analyzed with a chi-square test. An extreme-outcome effect should yield more reports of the extreme outcome than the non-extreme outcome. For the frequency judgments, data from a participant were excluded for a given door if the summed responses for that door fell outside of 75% to 150%. The frequency judgements were analyzed with t-tests. An extreme-outcome effect should yield higher percentage scores for the extreme outcome than for the non-extreme outcome. The three main hypotheses listed above were tested by comparing these memory reports across value and group for the risky extreme doors. The two secondary hypotheses were additionally evaluated by examining the memory reports for the risky neighbour doors. An extreme-outcome effect was observed when the

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Hypothesis 2 (*Value Distinctiveness*) was true. We therefore present them here as independent secondary hypotheses. The naming scheme for the hypotheses has also been added for clarity.

extremes (highest or lowest) were reported more often or judged as more frequent in the memory tests.

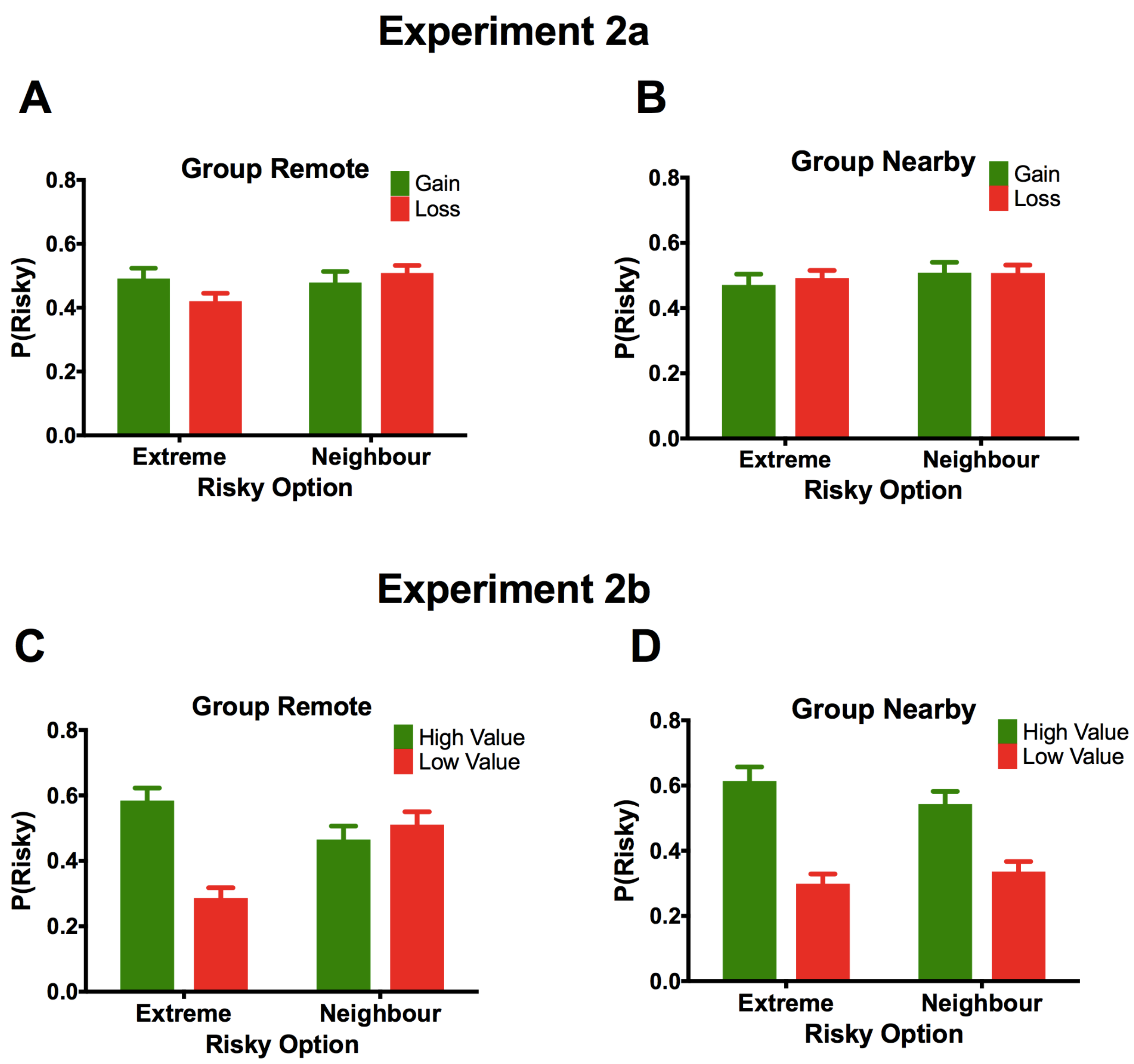

Figure 6. Proportion of choices of the risky option on decision trials between fixed and risky high-value options (green bars) and between fixed and risky low-value options (red bars) for the choices involving risky extreme doors or risky neighbour doors in: (A) Experiment 2a, Group Remote; (B) Group Nearby; (C) Experiment 2b, Group Remote; and (D) Group Nearby. Error bars are SEM.

Results

Risky choice. Figures 6A and 6B present the mean risky choice in Experiment 2a for each type of risky decision, for Group Remote and Group Nearby, respectively. Figures 6C and 6D present these same data for Experiment 2b.

The extreme-outcome effect (more risk seeking for relative gains than for relative losses) was weak in Experiment 2a (gains and losses), but was very strong in Experiment 2b (high- and low-value gains). In Group Remote of Experiment 2a, the extreme-outcome effect was weak and only marginally significant even with the directional hypothesis, with participants choosing the risky option only 7.1±4.2 (Mean±SEM) percentage points more often for gains than for losses, $t(102) = 1.66$, $p = .050$ (one-tailed), Cohen's $d = 0.16$. In Group Remote of Experiment 2b, there was a very robust extreme-outcome effect for extreme risky choice, with participants choosing the risky option 29.8±4.8 percentage points more often for high-value choices than for low-value choices, $t(61) = 6.23$, $p < .001$, $d = 0.79$. Thus, the *Extreme-Outcome-Reliability Hypothesis* was strongly supported by Experiment 2b, but only weakly supported by Experiment 2a.

As can be seen in Figure 6A and 6B, there were no consistent differences between groups in Exp 2a. The overall ANOVA on the extreme risky choices in Experiment 2a showed no significant effects (Value: $F(1,200) = 0.68$, $p = .41$, $\eta_p^2 =.003$; Group, $F(1,200) = 0.87$, $p = .35$, $\eta_p^2 = .004$; Value x Group, $F(1,200) = 2.27$, $p = .13$, $\eta_p^2 = .011$). Similarly, there were no significant effects for the ANOVA on the neighbour risky choices (Value: $F(1,200) = 0.26$, $p = .61$, $\eta_p^2 = .001$; Group, $F(1,200) = 0.23$, $p = .63$, $\eta_p^2 = .001$; Value x Group, $F(1,200) = .31$, $p = .581$, $\eta_p^2 = .002$).

Figure 6C and 6D show that there was a very strong extreme-outcome effect for both groups in Experiment 2b, supporting the *Edges Hypothesis* and contrary to the *Value-*

Distinctiveness Hypothesis. An ANOVA on the extreme risky choices showed a significant main effect of Value, $F(1,124) = 80.84$, $p < .001$, $\eta_p^2 = .40$, but not of Group, $F(1,124) = 0.30$, $p = .59$, $\eta_p^2 = .002$, and no significant interaction between Value and Group, $F(1,124) = 0.06$, $p = .81$, $\eta_p^2 =.00$.

In Experiment 2b, the two groups, however, differed in their responses to the risky neighbour doors. Figure 6C and 6D show how, in Group Nearby, choices for the risky neighbour doors were similar to those for the extreme doors, whereas, in Group Remote, choices were close to indifferent between both neighbour doors and the fixed outcomes. This pattern is corroborated by a significant main effect in the ANOVA of Value, $F(1,124) = 5.06$, $p = .026$, $\eta_p^2 = .039$, but not of Group, $F(1,124) = 1.48$, $p = .23$, $\eta_p^2 = .012$. In addition, there was a significant interaction between Value and Group, $F(1,124) = 12.38$, $p < .001$, $\eta_p^2 = .091$. This interaction reflected a significant extreme-outcome effect for the neighbour risky choices in Group Nearby (i.e., where the neighbour door outcomes were near the edges of the distribution), $t(63) = 4.25$, $p < .001$, $d = .53$, but not in Group Remote (where the neighbour doors outcomes were similar to the fixed outcomes), $t(61) = 0.86$, $p = .39$, $d = .11$. These results strongly support the *Edge-Proximity Hypothesis* and are contrary to the *Interference Hypothesis.*

Memory Tests

Risky Extreme Doors. Figures 7A and 7B show the percentages of participants who reported the "first outcome to come to mind" for the risky extreme doors in Experiment 2a. For Group Remote, significantly more participants reported the extreme outcome than the non-extreme outcome for both the gain door: $\chi^2(1, N=76) = 5.26$, $p = .022$, and the loss door: $\chi^2(1, N=78) = 18.51$, $p = <.0001$. Participants in Group Nearby were also significantly more likely to report the extreme outcome than the non-extreme outcome for the gain door, $\chi^2(1, N=58) = 5.59$,

p = .018, but only had a trend toward reporting the extreme outcome more than the non-extreme outcome for the loss door $\chi^2(1, N=50) = 2.88$, $p = .090$. Figures 7C and 7D show the judged frequency of each outcome for the extreme risky doors in Experiment 2a. Neither group showed a significant difference in the judged frequencies of the two outcomes that followed the risky extreme gain doors (Group Remote: mean difference -7.3±3.9%, $t(97) = 1.89$, $p = .062$, $d = 0.19$; Group Nearby: mean difference 1.6±3.4%, $t(88) = 0.64$, $p = .53$, $d = 0.067$). For the risky extreme loss door, however, both groups reliably reported the extreme outcome as having occurred more often than the non-extreme outcome (Group Remote, mean difference 19.1 ± 4.0%, $t(92) = 4.84$, $p < .001$, $d = 0.50$; Group Nearby, mean difference 15.2 ± 3.6%, $t(83) = 4.20$, $p < .001$, $d = 0.46$).

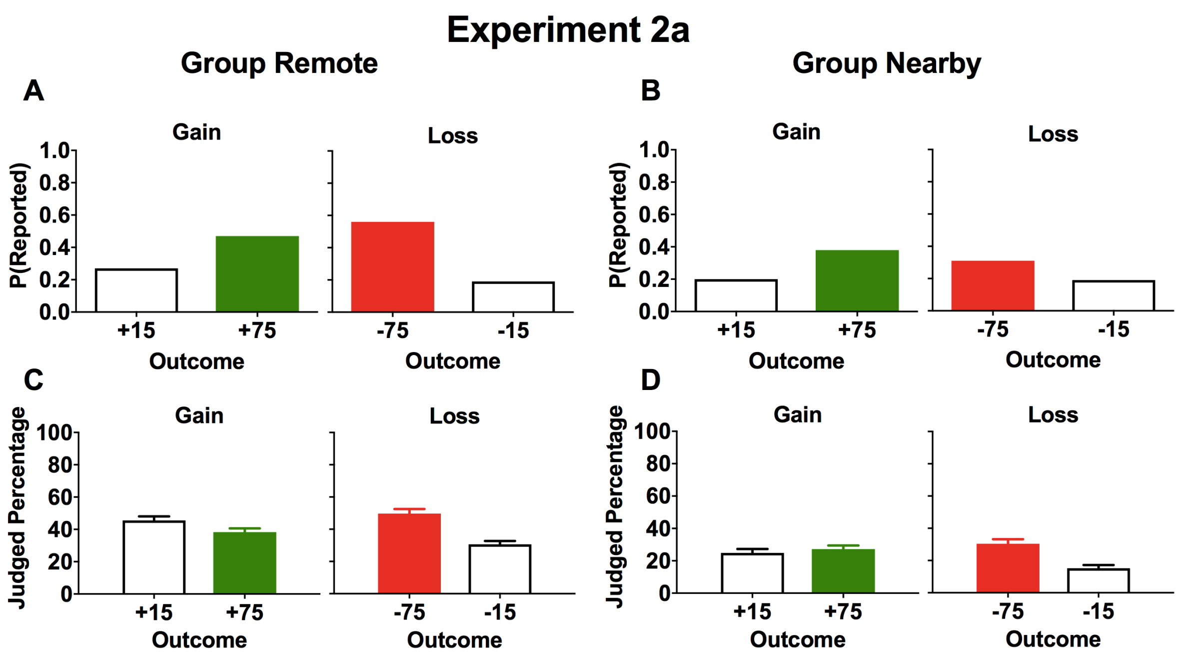

Figure 7. Results from self-report memory tests with the risky extreme doors in Experiment 2a. (A, B) The proportion of participants in each group who reported the extreme (filled red or green bars) and non-extreme values (white bars) as the "first outcome that came to mind" for each risky door. (C, D) The judged percentages for each risky door's outcome (±SEM). Note that the totals do not sum to 1 (top row) or 100 (bottom row) because participants also reported and assigned percentage to other outcomes.

Figures 8A and 8B show the percentages of participants who reported the “first outcome to come to mind” for the extreme risky doors in Experiment 2b.

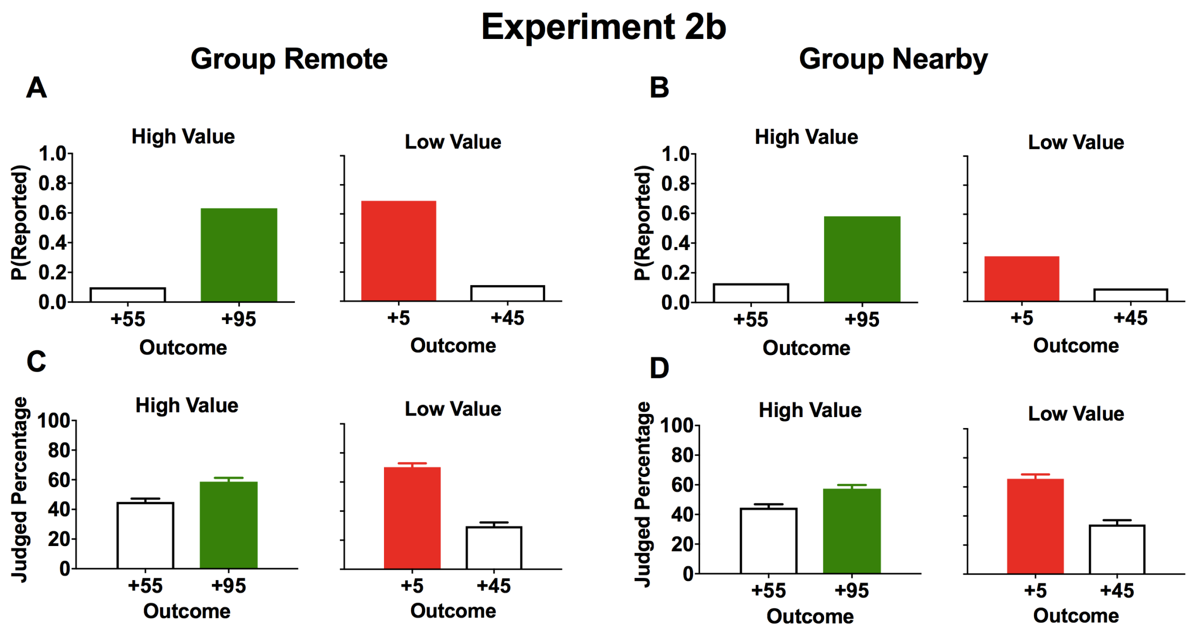

Figure 8. Results from self-report memory tests with the risky extreme doors in Experiment 2b. (A, B) The proportion of participants in each group who reported the extreme (filled red or green bars) and non-extreme values (white bars) as the “first outcome that came to mind” for each risky door. Note that the totals do not sum to 1 (top row) because participants also reported other outcomes. (C, D) The judged percentages for each risky door’s outcome (±SEM).

Participants in both groups were significantly more likely than chance to report the extreme outcomes for both the high- and low-value doors (Group Remote: high value $\chi^2(1, N=45) = 24.2$, $p < .0001$, low value, $\chi^2(1, N=50) = 25.9$, $p < .0001$; Group Nearby: high value, $\chi^2(1, N=45) = 18.7$, $p < .0001$, low value, $\chi^2(1, N=26) = 7.54$, $p = .006$), and the relative proportions in both groups were not reliably different from each other (high value: $\chi^2(1, N=90) = 0.38$, $p = .56$; low value: $\chi^2(1, N=76) = 0.99$, $p = .32$). Figures 8C and 8D show the judged frequency of each outcome for the extreme risky doors for Experiment 2b. Participants reported that the extreme outcome occurred more often in all cases (Group Remote: high-value, mean difference =13.8 ± 4.7%, $t(57) = 2.93$, $p = .005$, $d = 0.38$; low-value, mean difference = 40.6 ± 5.3%, $t(54) = 7.64$, $p < .001$, $d = 1.03$; Group Nearby: high-value, mean difference = 12.9 ± 4.8%, $t(62) = 2.70$, $p = .009$, $d = 0.34$; low-value, mean difference = 31.4 ± 6.1%, $t(55) = 5.17$, $p < .001$, $d = 0.69$).

Thus, although the two outcomes occurred with equal probability, people's subjective reports in both experiments indicated that the extreme low outcome occurred substantially more often than the non-extreme low outcome. In Experiment 2b, people additionally reported that the extreme high outcome occurred more often than the non-extreme high outcome. This pattern strongly supports the *Extreme-Outcome-Reliability* hypothesis. In addition, the overweighting of extremes in memory in most instances in Group Nearby is consistent with the *Edge* hypothesis and inconsistent with the *Distinctiveness* hypothesis.

Risky Neighbour Doors. Figure 9A and 9B display the first outcome reported for the risky neighbour doors in Experiment 2b (see Fig S2 for Exp 2a). In Group Remote, no outcome was reliably reported more often for either risky neighbour door, though there was a trend toward reporting the lower outcome for the low-value door (Low Value: $\chi^2(1, N=30) = 3.33$, $p = .068$; High Value: $\chi^2(1, N=29) = 0.03$, $p = .85$). In Group Nearby, the outcome (+6) one away from the low extreme was reported more often, $\chi^2(1, N=38) = 6.73$, $p = .009$, and there was also a trend toward reporting the outcome (+94) one away from the high extreme, $\chi^2(1, N=23) = 3.52$, $p = .061$. Note that the sample sizes here are all very small because, for each door, many participants reported values that never occurred with that door (see Supplemental Materials and Fig S5 for a detailed breakdown of these errors).

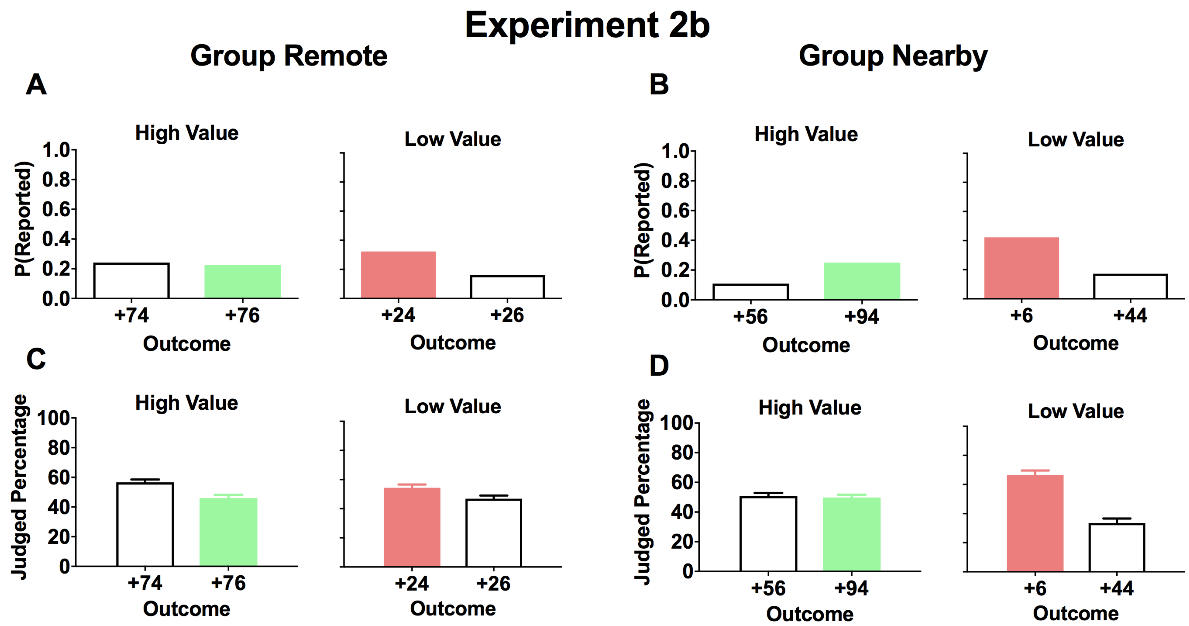

Figure 9. Results from self-report memory tests with the risky neighbour doors in Experiment 2b. (A, B) The proportion of participants in each group who reported the more extreme (light red or green bars) and non-extreme values (white bars) as the "first outcome that came to mind" for each risky door. Note that the totals do not sum to 1 (top row) because participants also reported other outcomes. (C, D) The judged percentages for each risky door's outcome (±SEM).

Figures 9C and 9D show the frequency judgments for the risky neighbour doors for Groups Remote and Nearby, respectively. In Group Remote, for the high-value door, participants judged the lower outcome (+74) as 10.6±3.8 (Mean±SEM) percentage points more frequent than the higher outcome (+76), $t(57) = 2.76$, $p = .008$, $d = 0.36$; for the low-value door, participants also judged the lower outcome (+24) as 7.5±4.3 percentage points more frequent than the higher outcome (+26), though this latter difference was not statistically reliable, $t(55) = 1.77$, $p = .08$, $d = 0.23$. This overweighting of the lower outcome in memory is consistent with previous results where none of the outcomes were extreme (Ludvig et al., 2015). In Group Nearby, for the low-value outcome, participants judged the outcome that was one away from the low extreme (+6) as 33.0±6.2 percentage points more frequent than the other possible outcome (+44) for that door,

$t(57) = 5.32$, $p < .001$, $d = 0.70$, but there was no significant difference (1.1±3.9%) in the judged frequencies for the high-value outcomes (+56/+94), $t(62) = 0.27$, $p > .5$, $d = 0.03$. The general trend toward the overweighting of the near-extreme outcome is consistent with the *Edge-Proximity* hypothesis, whereby outcomes near the edge of the distribution are all overweighted, and inconsistent with the *Interference* hypothesis

Discussion

The results of Experiment 2b clearly indicate that outcomes at the edges of the experienced distribution are overweighted in both memory and choice, even if they are very close to another neighbouring outcome. Thus, outcomes appear to be treated as extreme by virtue of their end position and not solely because of their distinctiveness based on distance to other outcomes (e.g., Brown et al., 2007).

Another interesting finding in Experiment 2b was that the neighbouring outcomes in Group Nearby were also overweighted in both risky choice and memory (see Fig 6D and Fig 9). This finding suggests that an outcome does not need to be at the exact edge of the distribution to be overweighted, but rather may only need to be near the edge. A detailed examination of the results from the memory tests indicated that some participants may have failed to discriminate between the extreme outcome and the adjacent neighbouring outcome; nevertheless, as reported in the Supplementary Materials, there was no significant correlation between the degree of confusion and risky choice. Although further research is needed to clarify exactly how close to the edge of a distribution an outcome needs to be for overweighting, these results clearly indicate that close proximity to a neighbouring value does not prevent the outcomes at the ends from being overweighted. These results indicate that distinctiveness based on separation from other values in the distribution (e.g., Brown et al., 2007; Neath et al., 2006) is not a necessary factor for the overweighting of extreme outcomes in experience-based risky choice.

One incidental finding in these experiments was a striking difference between the two experiments in the size of the extreme-outcome effect: specifically, the effect was weak in Experiment 2a (gains and losses) but extremely robust in Experiment 2b (high- and low-value gains). Although past research has shown reliable extreme-outcome effects with sets consisting of gains and losses (Ludvig & Spetch, 2011; Ludvig et al., 2014; Madan et al., 2014, 2015), the effect seems to be larger when the decision set includes all gains or all losses. In the former instance, attending to category information (i.e., gain or loss) may overshadow learning of the specific outcomes. Overshadowing by category information might have been particularly pronounced in this experiment because of the larger set of outcome values to learn (i.e., 5 gains and 5 losses) compared to our past studies, which typically had only 3 outcomes per category (e.g., Ludvig & Spetch, 2011). Future work will follow up on this incidental finding.

General Discussion

Together these experiments show that outcomes at or near the edges of a distribution are overweighted in memory and choice. The first two experiments extend previous evidence that overweighting of extremes occurs with sets consisting of all gains or all losses, and they rule out the possibility that differences in frequency are responsible for the overweighting of these outcomes. The second two experiments addressed the question of whether extreme outcomes are overweighted because of their placement at the ends of the distribution or because of their distance from other neighbouring values (e.g., Brown et al., 2007). Although Experiment 2a produced equivocal results, Experiment 2b showed very strong extreme-outcome effects for values at the edges of the distributions, even when those outcomes had directly adjacent neighbouring values. These results indicate that the extreme-outcome effect does not depend on the distinctiveness of the values and are consistent with other findings, which also suggest that edge values are particularly salient (e.g., Moon et al., 2015; Tsetsos et al., 2012). Interestingly, Group Nearby in Experiment 2a showed overweighting in memory and in risky choice both for the extreme risky outcomes and for the directly adjacent neighbouring outcomes. Thus, outcomes that are near the edges of a distribution can also function as extreme values, suggesting perhaps that the psychological representation of the edges is fuzzy (e.g., Reyna, 2012).

On the surface, these results contradict other findings from the memory literature, which suggest that memory strength depends on stimulus distinctiveness, due to the psychological proximity of other possible target items (Brown et al., 2007; Neath et al., 2006). In particular, the SIMPLE model of memory proposes that the distinctiveness of an item, and as a result memorability, is a function of proximity to its nearest neighbours. In this experiment, this supposition only held to a limited degree. Inserting immediately nearby items in Exp 2b (e.g., +94 to +95) did not eliminate the overweighting of the extreme outcomes in memory or choice. With the nearby neighbours, however, there was an apparent reduction in the overall frequency of reporting a correct outcome for the extreme doors in the first-outcome memory metrics (see Figs 7-8), though the extremes were still reported more often than non-extremes.

One major difference here from standard memory protocols is that the main task was a choice task, whereby distinctions between nearby outcomes were unnecessary or potentially even detrimental to effective performance. This choice procedure may thus have even encouraged the chunking of the very-nearby items into a single psychological unit (e.g., Miller, 1956), especially given the sheer number of outcomes (10) in Exp 2. For example, in Exp. 2B, perhaps +95 and

+94 were treated as an extreme chunk and +55 and +56 were treated as an intermediate chunk. According to this view, these extreme chunks are what stood out, rather than the individual outcomes, because they have fewer neighbouring chunks than the intermediate chunks. As a result, both extremes and their nearby neighbours became overweighted in choice and memory (Fig 6 and Fig 9). This alternate interpretation would seem to rescue the distance-based distinctiveness hypothesis by re-defining what counts as the relevant distance. One challenge for such an interpretation would be to specify exactly when neighbouring items would form chunks as opposed to act as individual items. Moreover, our analysis of the errors on the first-outcome memory tests in Exp 2B indicated that, even people who made no confusion errors (i.e., swapping an extreme for a neighbour or vice-versa) still showed a strong overweighting of the extremes. Presumably, these people kept the individual items separate in memory, yet they still overweighted the extremes and their neighbours.

These results have implications for theories of choice, especially those that rely on sampling outcomes from memory (e.g., Ratcliff & Smith, 2002; Shohamy & Daw, 2015; Stewart et al., 2006; Weber & Johnson, 2006). Here, memories for past outcomes are systematically biased such that the most extreme outcomes (and their nearby neighbours) are both better remembered and overweighted in choice (see Figs 6, 8, and 9). When modeling decisions based on past experience, sampling models would likely need to include a similar type of bias. Not all outcomes are equally likely to be retrieved and accumulated as evidence towards making a decision. There would seem to be a function relating proximity to the edge of the distribution to recall probability and choice weighting, though, at the moment the exact form of the function is underconstrained.

The present study adds to the literature from other domains, such as perception, learning, and memory, indicating that outcomes at the end of a range can have a privileged status (e.g., Castel et al., 2016; Jou, 2007, 2011; Kahneman et al., 1993; Lacouture, 1997; Moon et al., 2015). Why might this be the case? One possibility is that the edges of a distribution (whether based on time, space, or value) provide the boundary conditions for an experience. In these experiments, the extremes define for the participant how much money they could possibly stand to win or lose on any given trial. More generally, attending to the ranges or boundaries that define an experience may have general ecological relevance across many situations. For example, foraging animals would be well served to know the range of possible outcomes that a food patch might return, tracking both the best and worst returns. Such a memory for the range of outcomes could allow the adaptive coding of values, something observed in humans (e.g., Khaw et al., in press) and even encoded in the reward prediction errors reported by the dopamine system (Tobler et al., 2005).

Our results provide strong support for the extreme-outcome rule, which suggests that when people make experience-based risky choices, they are more likely to remember outcomes at the edges of the experienced distribution (Ludvig et al., 2014). The results also suggest a refinement to this rule, whereby proximity to the edge suffices for the overweighting in choice and memory. This memory bias leads people to be relatively more risk seeking for high-value choices (where the risky choice could lead to a good extreme) than for low-value choices (where the risky choice could leave to a bad extreme). This pattern of choice could have implications for real-world situations in which people make experience-based risky choices, such as in casino gambling. In such situations, people typically experience a mixture of big wins and small losses, and thus the saliency of the extremes in memory and choice might increase the likelihood of future gambling. Numerous interesting questions remain, however, about what constitutes the decision context, how stable such memory biases are, what other memory factors influence risky choice, and how this extreme-outcome bias interacts with the tendency to underweight rare events in experience-based choice (e.g., Hertwig et al., 2004).

Context Paragraph

The experiments reported here are part of a program of research to resolve how humans and other animals make risky choices when they learn about the odds and outcomes from experience. The notion that the overweighting of extreme outcomes may drive risky choice was originally proposed by Ludvig & Spetch, 2011 and expanded in later papers (Ludvig, Madan, & Spetch, 2014; Madan, Ludvig, & Spetch, 2014). Inspired by the peak-end effect (Kahneman, Fredrickson, Schreiber, & Redelmeier, 1993) and consistent with findings by Madan & Spetch, 2012, we hypothesized that values at the extremities of a distribution were more salient and better remembered. This paper presents research that supports this hypothesis, and it specifically tests opposing predictions from two hypotheses that could explain the previous extreme-outcome effects: (1) that the ends of the distribution are more salient, and (2) that items that are distinct from other values are more salient.

Author Note

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Table 1. Outcome values and extremes of the decision context in Experiments 1a (all gains) and 1b (all losses). All risky options have a 50% chance of either outcome.

	Low value		**High value**		**Extreme values**	
	Fixed	**Risky**	**Fixed**	**Risky**	**Low**	**High**
1a	+25	+5 or +45	+75	+55 or +95	+5	+95
1b	−75	−95 or −55	−25	−45 or −5	−95	−5

Table 2. List of options and possible outcomes for the two groups in Experiment 2. All Risky options have a 50/50 chance of either outcome.

Experiment 2a

Outcome	**Group Nearby**	**Group Remote**
Fixed Gain	+45	+45
Risky Extreme Gain	+15 or +75	+15 or +75
Risky Neighbour Gain	+16 or +74	+44 or +46
Fixed Loss	-45	-45
Risky Extreme Loss	-15 or -75	-15 or -75
Risky Neighbour Loss	-16 or -74	-44 or -46

Experiment 2b

Outcome	**Group Nearby**	**Group Remote**
Fixed High Value	+75	+75
Risky Extreme High Value	+55 or +95	+55 or +95
Risky Neighbour High Value	+56 or +94	+74 or +76
Fixed Low Value	+25	+25
Risky Extreme Low Value	+5 or +45	+5 or +45
Risky Neighbour Low Value	+6 or +44	+24 or +26

Supplementary Materials

Experiments 2a and 2b: Risky choice by block

Figure S1 shows the risky choice for the risky extreme doors for each Group and each outcome value across the 5 blocks in Experiments 2a and 2b. Behavior was fairly consistent across the session in both experiments.

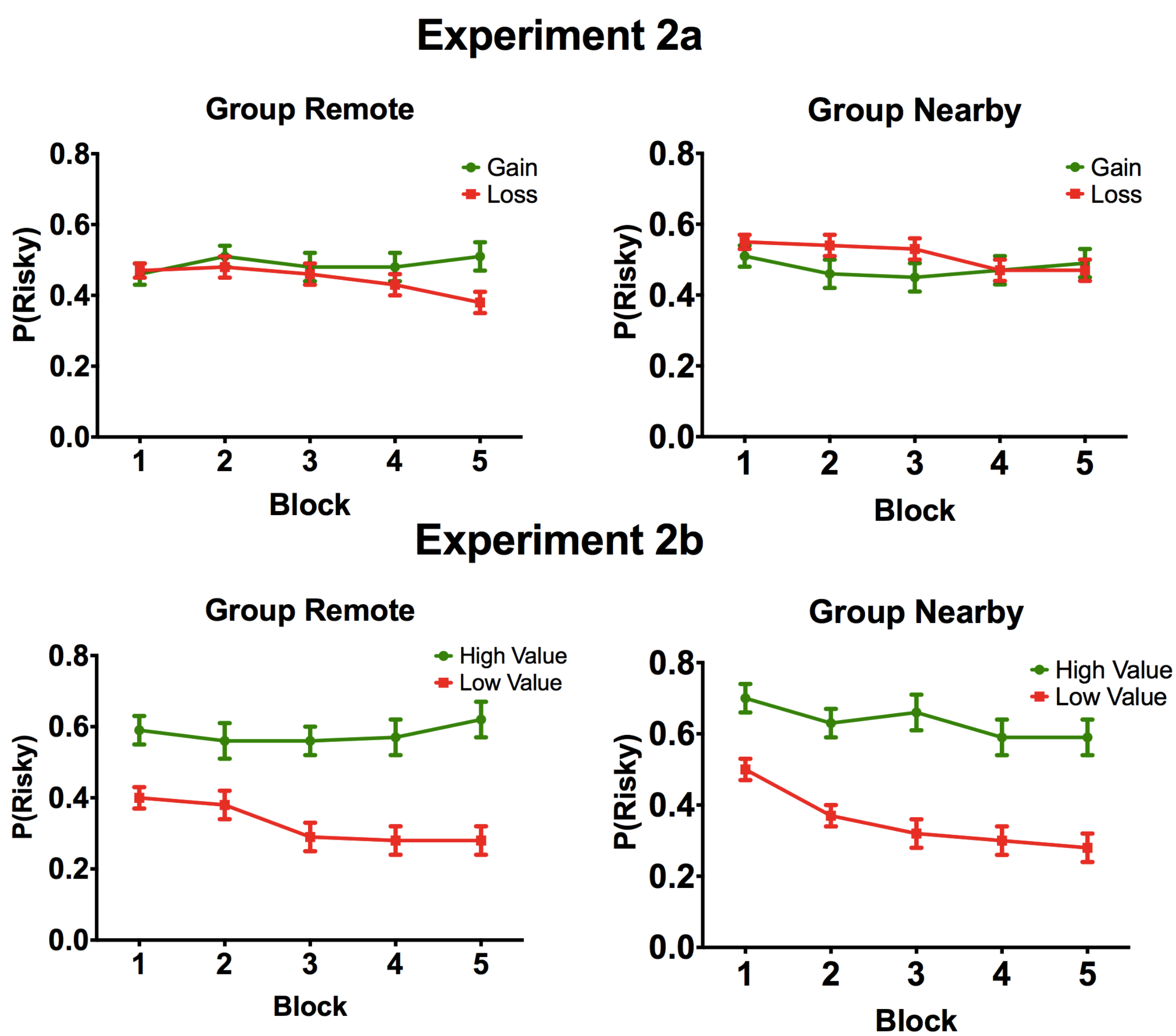

Figure S1. *Risky choice for the risky extreme doors across blocks for Groups Remote (left) and Nearby (right) in Experiments 2a (top) and 2b (bottom). Error bars are SEM.*

Experiment 2a: Memory Tests for Risky Neighbour Doors

Figures S2A and S2B show the first outcome reported for the risky neighbour doors in Experiment 2a.

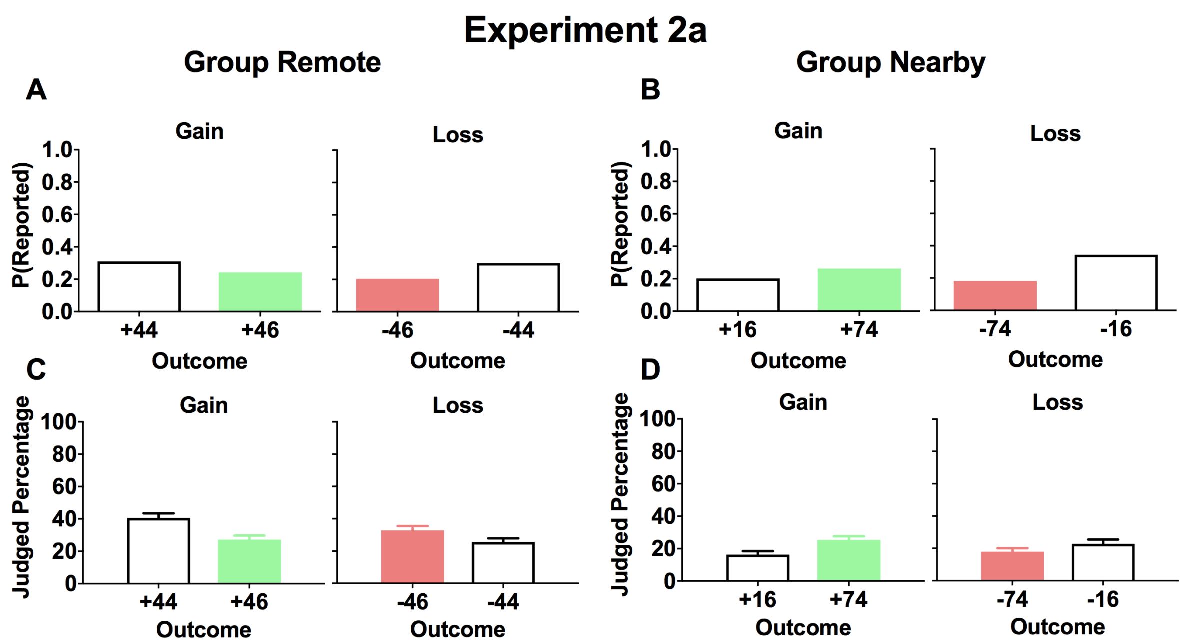

Figure S2. *Results from self-report memory tests with the risky neighbour doors in Experiment 2a. (A, B) The proportion of participants in each group who reported the more extreme (light red or green bars) and non-extreme values (white bars) as the "first outcome that came to mind" for each risky door. (C, D) The judged percentages for each risky door's outcome (±SEM). Note that the totals do not sum to 1 (top row) or 100 (bottom row) because participants also reported and assigned percentage to other outcomes.*

There was little visible difference for most doors, except for the risky gain door in Group Nearby, where participants reported the non-extreme outcome (-16) more frequently than the extreme outcome (-74), $\chi^2(1, N{=}52) = 4.92$, $p = .027$. There were no other reliable differences (Group Remote, Low Value: $\chi^2(1, N{=}52) = 1.92$, $p = .17$; Group Remote, High Value: $\chi^2(1, N{=}57) = 0.86$, $p = .35$; Group Nearby, High Value, $\chi^2(1, N{=}47) = 0.78$, $p = .38$). Figures S2C and S2D show how the frequency judgments for the risky neighbour doors were low across the board, with the summed frequency judgment for the two relevant doors never exceeding 68%.

These low estimates reflect how participants spread their estimates across all 10 available options, including 8 outcomes that never followed the door in question. Within those judgments, in Group Remote, participants judged the lower outcome (+44) as 13.4±4.5 (Mean±SEM) percentage points more frequent for the risky gain, $t(93) = 2.95$, $p = .004$, $d = .31$, with a similar trend (7.2±3.8%) for the risky loss, $t(94) = 1.89$, $p = .061$, $d = .19$. In Group Nearby, participants judged the outcome near the high extreme (+74) as 9.1±3.1 percentage points more frequent, $t(89) = 2.92$, $p = .004$, $d = .31$, but showed little difference (-4.9±3.3%) in the frequency judgment for the outcome (-74) that was near the low extreme, $t(86) = -1.49$, $p = .14$, $d = -.16$. Overall, there was not any clear, consistent pattern in the memory tests for the neighbor doors in Exp 2a.

Experiment 2b: Correlations between frequency judgments and risky choice

Figures S3 and S4 show the correlations between frequency judgment and risky choice for all 4 risky doors in both Group Remote (S3) and Group Nearby (S4) in Experiment 2b. These correlations are likely underpowered, given the sample sizes (54-62, depending on the exact correlation) and expected effect sizes from prior work (e.g., Madan et al., 2014, 2017), but they all trend in the direction that would be predicted by a memory-driven effect of extremes and their neighbours on risky choice. In Group Remote, the judged frequency for the high extreme (+95) positively correlated with risky choice ($r_p(55) = .41$, $p = .002$), whereas the judged frequency of the low extreme (+5) trended toward a negative correlation ($r_p(52) = -.25$, $p = .066$). There was no correlation with the judged frequency for the risky neighbor doors in Group Remote (High: $r_p(55) = .064$, $p = .64$; Low: $r_p(53) = -.074$, $p = .59$). In Group Nearby, for the high-value doors, frequency judgments for both the extreme and neighbour doors positively correlated with risky choice for those doors (Extreme: $r_p(59) = .28$, $p = .028$; Neighbour: $r_p(60) = .31$, $p = .015$), and there were also very mild, non-significant negative correlations for both risky low-value doors (Extreme: $r_p(52) = -.20$, $p = .14$; Neighbour: $r_p(55) = -.18$, $p = .19$).

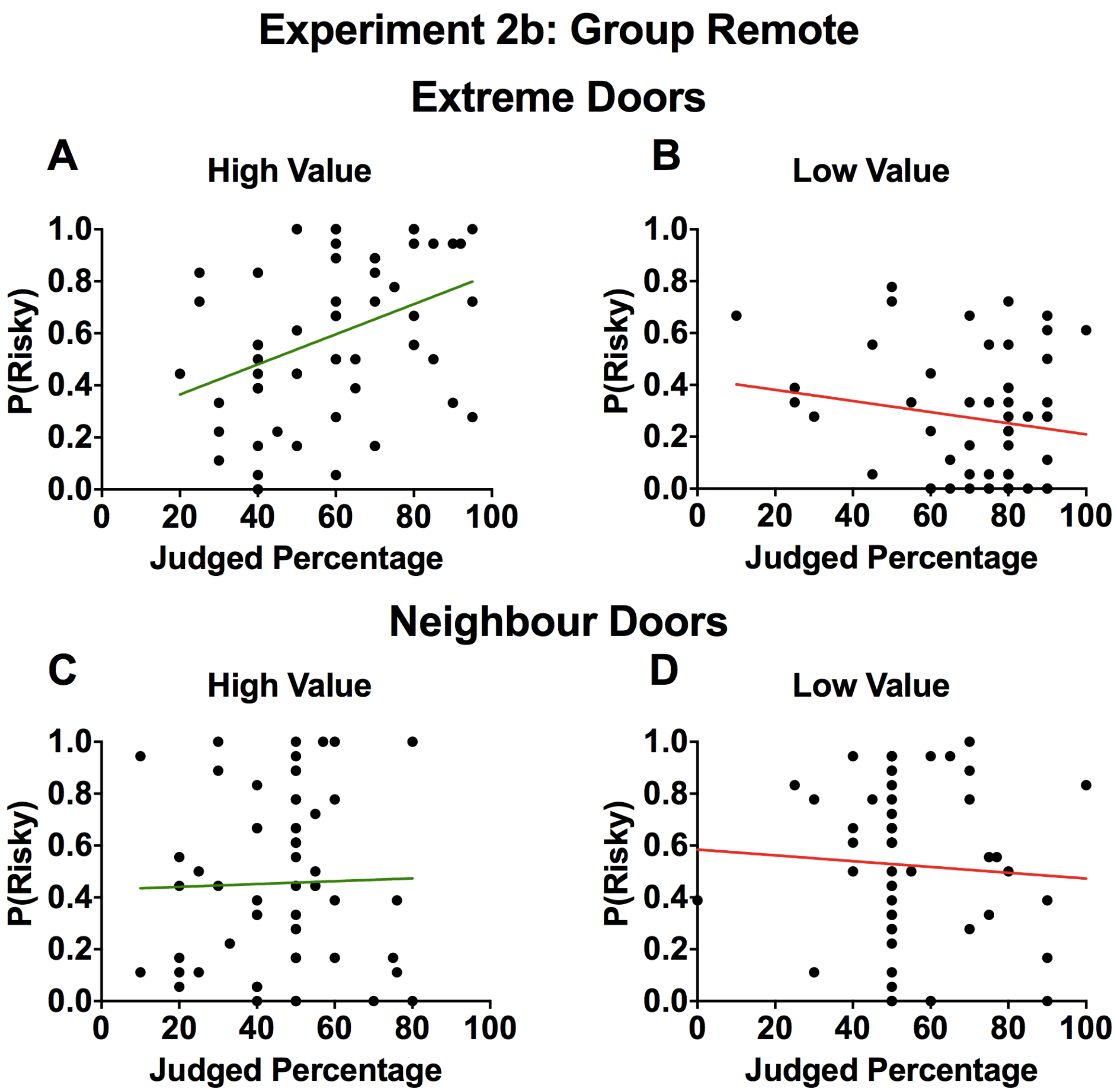

Figure S3. Scatterplots of the proportion of risky choices (averaged over last three blocks) as a function of the judged frequency of the risky extreme door for (A) high-value doors and (B) low-value doors (right) for Group Remote in Experiment 2b. (C-D) Same scatterplots for the risky neighbor doors. Each dot represents an individual participant.

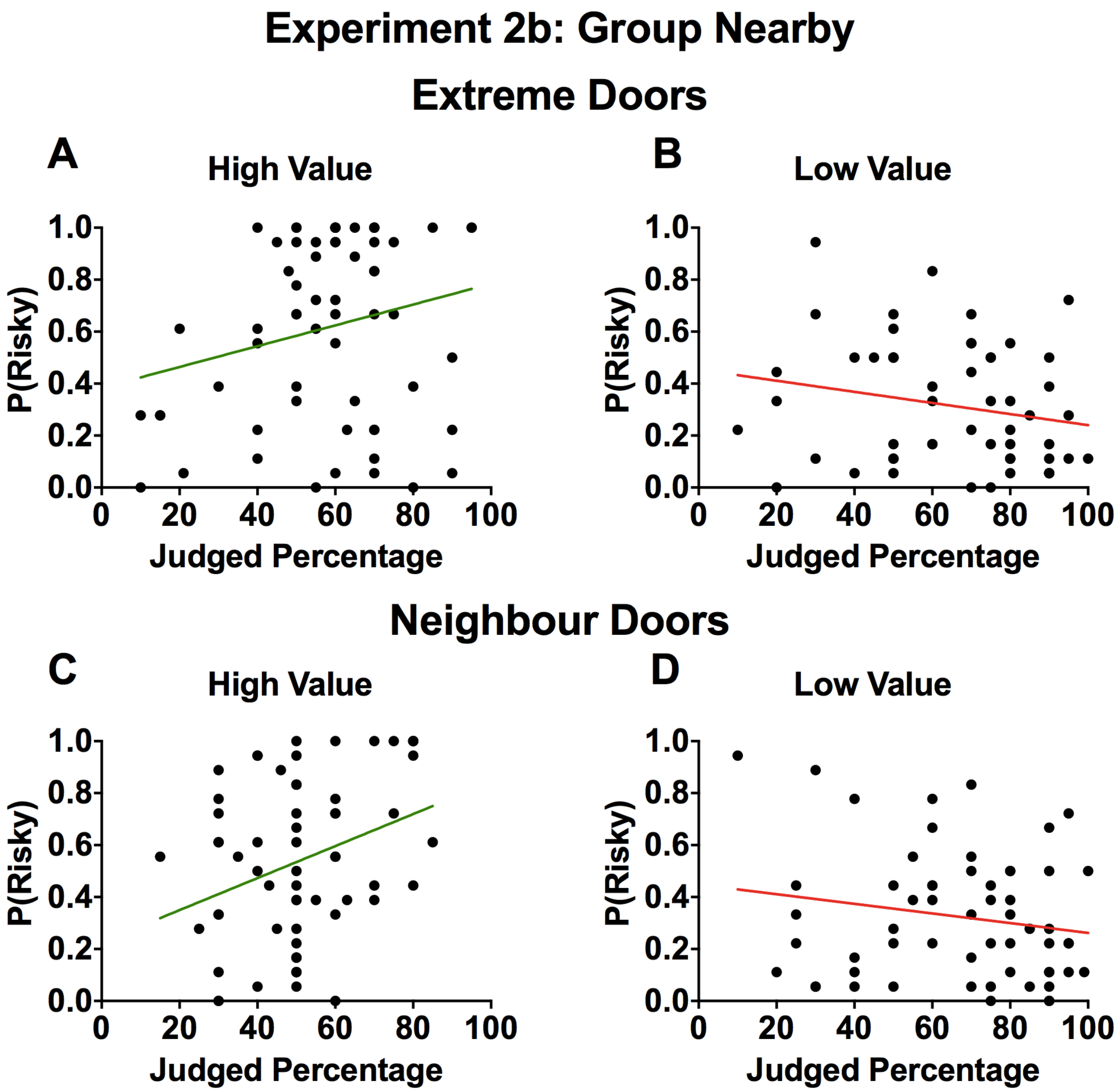

Figure S4. *Scatterplots of the proportion of risky choices (averaged over last three blocks) as a function of the judged frequency of the risky extreme door for (A) high-value doors and (B) low-value doors (right) for Group Nearby in Experiment 2b. (C-D) Same scatterplots for the risky neighbor doors. Each dot represents an individual participant.*

Experiment 2b: Analysis of Confusion between Nearby Neighbours and Extremes

This analysis was pre-registered at: https://osf.io/cnf8d/

In the choice task in Exp 2B, people behaved as though they overweighted the extremes (+5 and +95) in both groups (Group Nearby and Group Remote), choosing more riskily for high-value than low-value options. In Group Nearby, they also chose more riskily for the high-value neighbors than the low-value neighbors. This pattern suggests that the Nearby Neighbour outcomes (+6 and +94) might also have been overweighted (*Hypothesis #1*).

After preliminary analysis of the memory results for both Exp 2A and 2B, we observed that the memory for extreme outcomes was generally overweighted in both the first-outcome test and the frequency-judgment test (see Figs 7 and 8 in main text). In addition, as shown in Figure S5, we also observed that, in the first-outcome test, errors often consisted of reporting the outcome that was only 1 digit away (e.g., +5 instead of +6).

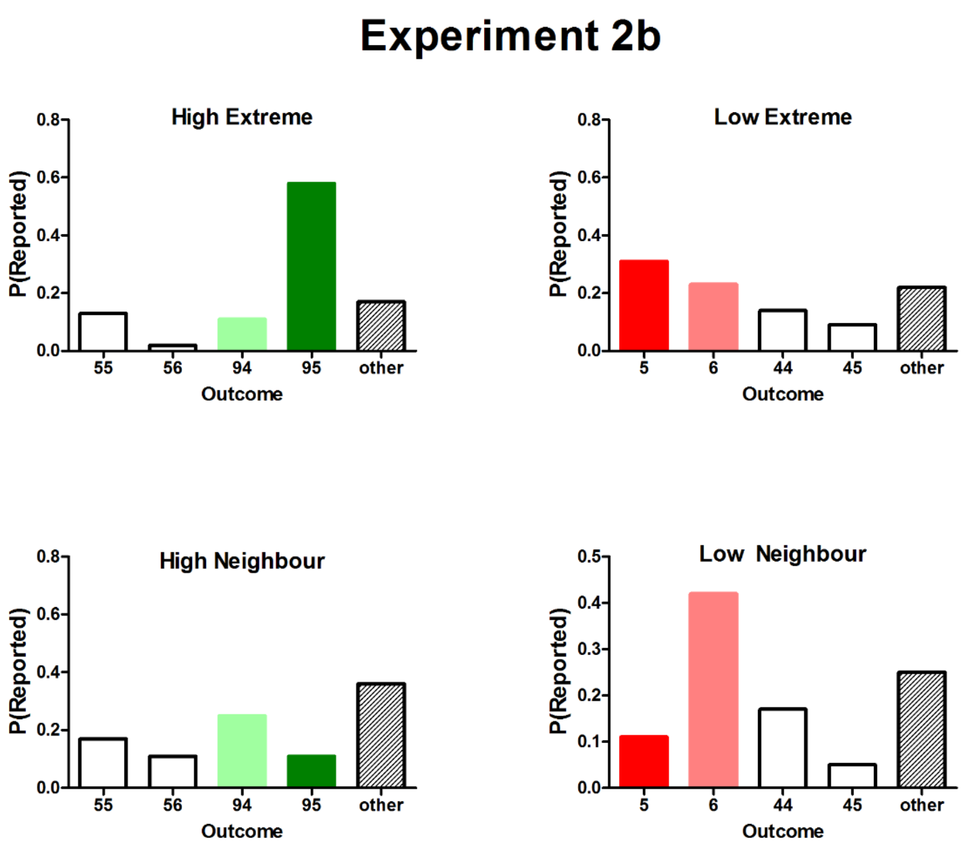

Figure S5. Proportion of participants reporting each value as the first outcome to come to mind for the high extreme (top left), low extreme (top right), high neighbour (bottom left) and low neighbour (bottom right) doors in Experiment 2b.

This suggested that perhaps in the Nearby Neighbour choices (e.g., +6/+44 vs. +25), there was a degree of confusion in memory between the Nearby Neighbour (e.g., +6) and the Extreme outcome (e.g., +5). So, the Nearby Neighbour may not have been directly overweighted, but rather the apparent overweighting might be due to confusion with the extreme outcomes. Then, as a result of the overweighting of extreme outcomes, there would be more risky choice for the Nearby Neighbour doors with high-value than with low-value outcomes (*Hypothesis #2*).

To distinguish these two hypotheses as to the source of the apparent overweighting, we created a "confusability score" for each participant in Experiment 2b[1] by counting the number of times they responded with a number that was one off from a possible outcome in the first-outcome questions. This score was created for both the Neighbour doors and the Extreme doors. Table S1 details exactly what counted as a confusion answer for each door for Exp 2B.

Table S1. Correct and confusion answers for each door in 2B.

Door	**Correct Responses**	**Confusion Responses**
High-Value Extreme	+55 or +95	+56 or +94
High-Value Neighbour	+56 or +94	+55 or +95
Low-Value Extreme	+5 or +45	+6 or +44
Low-Value Neighbour	+6 or +44	+5 or +45

The extreme doors and neighbor doors were analyzed separately. There were 2 total first-outcome questions for both the extreme doors and neighbour doors (see Table 1), so the confusability index could range from 0 to 2 for each individual, depending on the answers provided. We then correlated that confusability score for each door type (extreme or neighbour) against the degree to which each individual showed more risky choice for high-value doors than low-value doors (i.e., size of the reflection effect) for the corresponding doors.

The *overweighted-neighbours hypothesis* (Hyp #1) predicts there will be overweighting of the neighbours even in the subset of participants with a confusability score of 0. The *memory-confusability hypothesis* (Hyp #2) predicts that there will be a correlation between the confusability scores and risky choice.

The mean (±SEM) confusion scores were 0.50 (±0.08) for the extreme doors and 0.44 (±0.07) for the neighbour doors. The correlations between these confusion scores and risky choice was significant for the extreme doors, $r(63)= 0.31$, $p = .012$, but not for the neighbour doors, $r(63)= -0.05$, $p = .69$. The reversed reflection effect for extreme doors was significant even for the 36 participants who showed confusability scores of 0 (mean= 23.9±5.5%, $t(35) =4.33$, $p<.001$), and the reversed reflection effect was also significant for the neighbour doors for the 39 participants who showed confusability scores of 0 (mean=23.8%±6.5%, $t(38)=3.68$, $p<.001$).

In sum, these results suggested that confusion may have played some role, but the overweighting was clearly not driven solely by confusion between the extreme and nearby neighbour doors.

Note:

[1] In our pre-registered analysis we indicated that we would also conduct this analysis for Experiment 2a. Because there was no reverse reflection effect for the neighbour doors in this experiment, however, this analysis did not seem useful.